

Contamination investigation and multi-dimensional risk assessment for ochratoxin A in grain products

Guangyun Chen

Jiangsu University

Junjian Li

Jiangsu University

Guizhu Wu

Jiangsu University

Daolin Du

Jiangsu University

Ming Li

`liming@ujs.edu.cn`

Jiangsu University

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Abstract

Ochratoxin A (OTA) contamination in grain products poses substantial public health concerns. This study assessed OTA contamination and associated multi-dimensional health risks in major grain products widely consumed in the Yangtze River Delta of China. The OTA contamination in 324 samples of wheat, peanuts, corn, and soybeans was determined by LC-MS/MS. Then, a comprehensive risk assessment was conducted by performing pollution index (PI), exceedance rate (ER), margin of exposure (MOE), and percentage of provisional tolerable weekly intake (%PTWI). The overall OTA detection rate was 11.7%. Corn showed the highest contamination, with a positive rate of 16.7% and concentrations ranging from 0.18 ng/g to 5.16 ng/g, representing the only commodity with samples exceeding the regulatory limit with PI value of 1.03. Risk assessment showed that the mean %PTWI for adults aged 18–44 consuming corn reached 104.3% when a single high-concentration outlier was included, exceeding the safety threshold. However, the median (51.9%) and outlier-excluded mean (51.5%) remained below the threshold, indicating that the exceedance is driven by an isolated extreme sample rather than typical exposure levels. Two corn samples had tumor MOE values below 10000, suggesting a concern for further investigation, but not constituting a definitive carcinogenic risk for the general population. In contrast, wheat, peanuts, and soybeans showed low contamination levels and acceptable risk profiles across all age groups. Therefore, corn may deserve increased attention in routine OTA monitoring efforts in the Yangtze River Delta, and age-specific dietary considerations could be further explored if needed.

1. Introduction

Ochratoxin A (OTA) is a potent secondary metabolite produced by *Aspergillus* and *Penicillium* species (Asafari et al., 2025; Oluwakayode et al., 2024). It is considered one of the most concerning mycotoxins in the global food supply chain (Li et al., 2024a). OTA contaminates a diverse array of products including cereals, coffee, cocoa, wine, dried fruits, and spices, posing considerable health risks to humans and animals (Samuel et al., 2021; Zhang et al., 2024; Ai et al., 2025). Toxicological studies have established that exposure to OTA is associated with various adverse health effects, including nephrotoxicity, hepatotoxicity, immunotoxicity, teratogenicity, and carcinogenicity (Lv et al., 2025; Zheng et al., 2025). The kidney is the primary target organ, where OTA accumulates owing to its prolonged half-life in humans, which is approximately 35 days, and its high affinity for plasma proteins (Lee et al., 2024). OTA toxicity is mechanistically linked to several pathways, including lipid peroxidation, inhibition of protein synthesis, DNA damage, oxidative stress, and mitochondrial dysfunction (Malir et al., 2023; Zhao et al., 2024a; Zhou et al., 2024). OTA has been classified as a Group 2B carcinogen, indicating that it is possibly carcinogenic to humans, based on substantial evidence of carcinogenicity derived from animal studies (Zhao et al., 2024). Given its prevalence in food processing, along with its thermal stability and degradability, OTA contamination represents an ongoing threat to global food safety and public health (Li et al., 2024a; Lin et al., 2025; Zhang et al., 2024a).

To protect consumer health, international bodies and national authorities have established regulatory limits for ochratoxin A. The European Union has set maximum levels for OTA in various food grains,

including 5.0 ng/g for unprocessed cereals, 3.0 ng/g for processed cereal products, 8.0 ng/g for roasted coffee beans, and 2.0 ng/g for instant coffee (Zheng et al., 2025). Stricter limits of 0.5 ng/g are imposed on cereal-based foods intended for infants and young children (European Commission, 2006). The Codex Alimentarius Commission has adopted practices to prevent and reduce OTA in cocoa and coffee, highlighting the need for internationally harmonized food safety standards (Zhang et al., 2025). The Chinese national standard specifies a limit of 5.0 ng/g for OTA in grains and their products (China National Standard, 2024). Despite these regulatory frameworks, OTA contamination remains a persistent global food safety concern, with recent data indicating an upward trend.

The global prevalence of OTA in food grains exhibits significant regional variations influenced by climatic, grain, storage, and socio-economic factors (Ren et al., 2024). In China, the OTA positive rate in rice, wheat, and corn ranged from 30% to 50%. In Africa, cocoa showed 91.5% OTA positivity with concentrations up to 33.23 ng/g, while dried fruits reached 89% positivity (Emir et al., 2025; Mannani et al., 2023). In Europe, cereals and infant cereals presented OTA levels of 0.1 to 9.3 ng/g with positive rates from 11% to 89%. In Italy, chili and spices contained 10 to 17 ng/g OTA (Lešić et al., 2025). In Lebanon, rice, spices, and milk showed 100% OTA positivity (Rizk et al., 2025). These regional surveys consistently demonstrate that OTA contamination is widespread globally with high detection rates, and the potential risk is considerable (Tabarani et al., 2023).

OTA risk assessments globally consistently use exposure margin, provisional tolerable weekly intake, and hazard quotient. In Northern Vietnam, dietary exposure assessment based on corn consumption showed that ochratoxin A intake among local populations exceeded the provisional tolerable weekly intake by 2.4–3.6 times (Hladik et al., 2024). In Croatia, non-neoplastic risk assessment using MOE indicated that 4.15% of consumers faced health risks from traditional meat products (Lešić et al., 2025). In Turkey, MOE calculation for high consumers of dried mulberries yielded a value of 3810, suggesting potential neoplastic risks (Caba & Kabak, 2025). In Italy, MOE-based risk assessment of OTA from meat showed that infants and children had MOE values below 200, representing a high-risk scenario (Annunziata et al., 2025). In Lebanon, biomonitoring was adopted to confirm chronic OTA exposure in the general population (Rizk et al., 2025). In the Netherlands, serum-based human biomonitoring and MOE analysis revealed that most pregnant women had safe exposure, but one individual showed less than 10000 of MOE (McKeon et al., 2024). In Belgium, cumulative risk assessment with combined MOE showed high consumers faced potential risks from rice, flour, and biscuits (Meerpoel et al., 2021). The dietary exposure and margin of safety assessments indicated that the overall risk was negligible, whereas infants and young children with high oat cereal consumption had the highest exposure (Tabarani et al., 2023). These studies demonstrate that OTA risk assessment frameworks vary slightly by region but consistently confirm widespread contamination and potential health hazards. These studies underscore the essential need for comprehensive, multi-dimensional risk assessments that combine contamination data with population-specific consumption patterns to identify high-risk grains and vulnerable subpopulations (Li et al., 2024; Yang et al., 2026).

Given the significant health risks associated with OTA contamination and the limitations of current data for the Yangtze River Delta region of China, this study aims to systematically investigate OTA contamination in major grain products using a validated analytical method (Scheme 1). The liquid chromatography-tandem mass spectrometry (LC-MS/MS) was used to determine OTA levels in 324 samples of wheat, peanuts, corn, and soybeans collected from this region, thereby characterizing the contamination levels and distribution patterns. In addition, a multi-dimensional risk assessment was conducted by integrating four indicators, namely pollution index, exceedance rate, margin of exposure, and provisional tolerable weekly intake percentage, to comprehensively assess dietary exposure risks across age groups. By identifying high-risk grains and sensitive populations, this study provides a scientific basis for targeted regulatory interventions and dietary recommendations. The integrated framework combining detection, multidimensional risk assessment, and tiered control established herein offers a transferable paradigm for mycotoxin management that can be adapted to other regions and contaminants.

2. Materials and methods

2.1 Reagents and instruments

The reagents of acetonitrile, methanol, formic acid, ammonium formate, and sodium chloride, which used for sample pretreatment and instrument mobile phase, were purchased from Aladdin Reagent Co., Ltd. (Shanghai, China). The OTA immunoaffinity column for purification procedure was supplied by Beijing Huaan Magnech Bio-tech Co., Ltd. (Beijing, China). The MF-Millipore™ 0.22 μm filter membranes were obtained from Sigma-Aldrich Co., Ltd. (Shanghai, China). The RE-5299 rotatory evaporator and KQ5200E ultrasonic extraction apparatus were bought from Huachen Instrument Factory Co., Ltd. (Zhengzhou, China). The liquid chromatography-tandem mass spectrometer (LC-MS/MS) equipped with an electrospray ionization (ESI) source was from Shimadzu Corporation (Kyoto, Japan). The reversed-phase chromatographic column (Shim-pack XR-ODSIII, 1.6 μm , 50 mm $\times$ 2.0 mm) was also provided by Shimadzu Corporation (Kyoto, Japan).

2.2 Sample collection

A total of 324 grain samples, comprising 81 wheat, 86 peanut, 78 corn, and 79 soybean specimens, were collected from the Yangtze River Delta region (spanning Shanghai, Jiangsu, Zhejiang, and Anhui provinces) between January 2025 and March 2026. The four grain types were specifically selected based on their dominant roles in the regional dietary structure and their well-documented susceptibility to ochratoxin A contamination as reported in the literature. Among these, wheat and corn serve as primary staples; peanuts are widely consumed as snacks and utilized as a source of cooking oil; and soybeans are fundamental ingredients in processed foods. To ensure a representative snapshot of the entire supply chain, sampling sites were strategically distributed across 12 major cities in the Yangtze River Delta, covering a diverse range of sources including production origins (farms and storage facilities), retail markets, and food safety surveillance points. All samples were collected in appropriate

quantities, sealed in sterile sampling bags, labeled with detailed geographic and temporal information, and stored under low-temperature and light-protected conditions prior to transportation and pretreatment, in accordance with the standard for cereal sampling (International Organization for Standardization, 2009).

2.3 OTA detection

The determination of OTA was performed through LC-MS/MS system (Qiu et al., 2023). The collected samples (entirely crushed, 2.0 g) were extracted with 10 mL of mixture solution (acetonitrile, water, and formic acid mixed at a volume ratio of 80:19:1, containing 2.0 g of sodium chloride) (Lv et al., 2025). The mixture was subjected to ultrasonic extraction and followed centrifugation. The supernatant was evaporated to dryness under nitrogen. The residue was then purified using an OTA immunoaffinity column. Following elution, the purified fraction was evaporated to dryness. The resulting residue was redissolved in a methanol-water mixture (0.5 mL, 1:1, v/v) and subsequently filtered through the 0.22 μ m filter membrane.

The purified extract (10 μ L) was carried out chromatographic separation on a reversed-phase column with a binary mobile phase system (Gao et al., 2025). The phase-A consisted of 5.0 mmol/L ammonium formate in water containing 0.5% formic acid, while phase-B comprised methanol and acetonitrile mixed at a 50:50 volume ratio supplemented with 0.5% formic acid and 5.0 mmol/L ammonium formate. Gradient elution was performed at a flow rate of 0.3 mL/min. The mass spectrometric quantitation was achieved via an ESI mode, with the parent ion monitored at m/z 404.2, the characteristic transitions at m/z 387.1 for qualitative analysis and m/z 105.2 for quantitative analysis (Gao et al., 2025a; Yang et al., 2026).

Prior to sample analysis, the analytical method was fully validated in grain matrices. The validation parameters, including limit of detection (LOD), limit of quantification (LOQ), linear range, correlation coefficient (R^2), and recovery rate, are detailed in Table S1 of Supplementary Material.

2.4 Contamination investigation

All samples were analyzed in triplicate to obtain detailed OTA contamination levels. Based on the investigation of OTA levels in grain products, all samples were categorized according to contamination degree, positive detection rate, and exceedance of regulatory limits. The overall detection rate and concentration ranges for each grain type were calculated to characterize the occurrence pattern of OTA in the Yangtze River Delta region in China.

2.5 Risk assessment

The multi-dimensional and comprehensive risk assessment was conducted using four complementary indicators: PI, ER, MOE, and %PTWI. These indicators were used to assess both contamination characteristics and health risks, including tumor and non-tumor effects as well as chronic cumulative risks associated with dietary OTA exposure.

The calculation formulas for each indicator are presented in Table 1. The EDI value was calculated using the following equation: $EDI = (COTA \times IR \times EF \times ED) / (BW \times AT)$. Where, COTA is the OTA concentration in ng/g, IR is the daily ingestion rate of grain products derived, EF is the exposure frequency set at 365 days/year, ED is the exposure duration of 70 years, BW is the age-specific body weight based on Chinese population data, and AT is the averaging time of 70 years $\times$ 365 days (Al-Aizari et al., 2023). Age groups were defined as 2–6, 7–12, 13–17, 18–44, 45–59, and $\geq$ 60 years. The safety thresholds were established as $MOE < 10000$ for tumorigenic risk and $MOE < 200$ for non-tumorigenic risk, as recommended by the European Food Safety Authority (EFSA) Panel on Contaminants in the Food Chain (Dieter et al., 2020). The benchmark dose lower confidence limit ($BMDL_{10}$) values of 14.5 ng/kg bw/day for tumorigenic effects and 4.8 ng/kg bw/day for non-tumorigenic effects were adopted from the EFSA scientific opinion (Dieter et al., 2020). The provisional tolerable weekly intake (PTWI) of 100 ng/kg bw/week was established by the Joint FAO/WHO Expert Committee on Food Additives (JECFA). It should be noted that this study concurrently applied the JECFA PTWI (100 ng/kg bw/week) and the EFSA 2020 $BMDL_{10}$ reference values (14.5 ng/kg bw/day for tumor effects and 4.8 ng/kg bw/day for non-tumor effects), which differ fundamentally in their conceptual basis and derivation methodologies. These two benchmarks are presented in parallel to facilitate comparison with previous literature, rather than to equate them; the primary conclusions are drawn based on the more stringent EFSA 2020 reference values. Furthermore, both MOE and %PTWI calculations were based on OTA-positive samples ($> LOQ$), with non-detects ($< LOQ$) treated as zero and excluded from mean calculations to avoid dilution of risk estimates by a large number of non-detects. A sensitivity analysis for %PTWI was also performed under five scenarios (mean including outlier, median, P75, P95, and mean excluding the outlier) to verify the robustness of the results. All age-specific body weight (BW) and daily ingestion rate (IR) data used in the EDI calculation were derived from the China National Nutrition and Health Survey (CNNHS) and are detailed in Table S2.

Table 1
The summary of risk assessment indicators for OTA contamination.

Indicator	Formula	Description
PI	$PI = C_{OTA} / S_{limit}$	C_{OTA} : Concentration of detected OTA (ng/g) S_{limit} : Safety limit (5.0 ng/g)
ER	$ER = N_{exceed} / N_{total} \times 100\%$	N_{exceed} : Number of samples exceeding the limit N_{total} : Number of total samples
Tumor MOE	$MOE = BMDL_{10} / EDI$	$BMDL_{10} = 14.5 \text{ ng/kg bw/day}$ EDI: Estimated daily intake
Non-tumor MOE	$MOE = BMDL_{10} / EDI$	$BMDL_{10} = 4.8 \text{ ng/kg bw/day}$
%PTWI	$\%PTWI = EWI / PTWI \times 100\%$	$PTWI = 100 \text{ ng/kg bw/week}$ EWI: Estimated weekly intake

The corresponding classification and evaluation criteria are provided in Table S3, offering a unified quantitative framework for subsequent statistical analysis and risk grading. Specifically, PI and ER were applied to evaluate the general contamination level and the distribution characteristics of OTA exceeding regulatory limits across different grain types (Caba et al., 2025). The MOE approach was applied to quantitatively characterize both tumorigenic and non-tumorigenic health hazards posed by long-term dietary OTA intake, based on the measured OTA concentrations and local cereal consumption data (Annunziata et al., 2025). The %PTWI was adopted to reflect the chronic cumulative exposure of the population through daily diet (Lešić et al., 2025).

The primary objective of employing these four indicators was to achieve a systematic and comprehensive evaluation of OTA contamination levels, exceedance patterns, and associated dietary exposure risks. This approach first objectively reveals the contamination patterns and spatial distribution of OTA in major regional cereal products. It then clarifies the variations in tumor and non-tumor health risks across different population groups, and further characterizes the residents' chronic cumulative exposure levels. The findings provide a solid data foundation and theoretical support for the development of targeted OTA prevention and control strategies, the optimization of food safety regulatory measures, and the protection of resident dietary health and food safety.

3. Results and discussion

3.1 OTA contamination levels and distribution

A total of 324 grain samples were collected from the Yangtze River Delta region of China and subjected to quantitative analysis of OTA using LC-MS/MS. The analytical method has been fully validated to

ensure reliable and accurate detection in complex grain matrices. The detailed OTA contamination data are displayed in the Table S4 and Table 2.

Table 2
The OTA contamination for the collected samples.

Item	Wheat	Peanut	Corn	Soybean
Total samples (No.)	81	86	78	79
Positive samples (No.)	6	8	13	11
Exceedance samples (No.)	0	0	1	0
Average Conc. (ng/g)	0.33	0.56	0.78	0.48
Conc. range (ng/g)	0.10–0.81	0.24–0.89	0.18–5.16	0.05–1.11

Among all samples, 38 were identified as OTA-positive, resulting in an overall detection rate of 11.7%. Significant differences in contamination levels were observed across different grain types. Corn exhibited the most severe contamination, with a detection rate of 16.7% and OTA concentrations ranging from 0.18 to 5.16 ng/g. Notably, corn was the only commodity in which a sample exceeded the national regulatory limit. Wheat showed the lowest detection rate of 7.4%, with OTA concentrations ranging from 0.10 to 0.81 ng/g and no samples exceeding the regulatory threshold. Peanuts and soybeans displayed moderate contamination, with detection rates of 9.3% and 14%, and all measured concentrations remained within the specified safety limits. The concentration distribution of all OTA-positive samples is presented in Fig. 1. Among positive samples, 45% contained OTA at levels below 0.3 ng/g, and only 7.9% exceeded 1 ng/g, indicating that contamination across the region was generally low and mild. Corn exhibited the widest concentration range and the highest proportion of high-level contamination. Peanuts exhibited a relatively narrow and concentrated contamination range. In contrast, wheat and soybeans were characterized predominantly by low contamination levels.

The distribution characteristics of OTA contamination across different grain types are presented in the corresponding figure (Fig. 2). Wheat exhibited the lowest median and mean concentrations, with data points tightly clustered and no outliers detected. In contrast, peanuts, corn, and soybeans showed broader concentration dispersion and higher median contamination levels. Notably, an extreme outlier value of 5.16 ng/g was detected in a single corn sample. This value substantially elevated the mean contamination level for corn and suggested the occurrence of localized high-risk contamination. Although the median concentrations for all grain types remained below 0.5 ng/g, the wide concentration range and the presence of an outlier in corn suggested a higher OTA contamination risk compared to wheat, peanuts, and soybeans.

In comparison with global surveys of OTA contamination in grains, the detection frequencies and concentration ranges obtained in the present study align with the background levels documented in other regions, suggesting the absence of widespread severe contamination. Nevertheless, the

occurrence of highly contaminated individual corn samples indicates potential localized health risks. The detection of an extreme outlier in corn (5.16 ng/g) validates the effectiveness of our comprehensive sampling strategy covering multiple supply chain nodes, demonstrating that extending the sampling scope to production and storage stages is of significant value for a thorough assessment of contamination status.

3.2 Pollution index and exceedance rate

The evaluation based on the pollution index revealed that all samples had values below 1.0, except one corn sample labeled Corn 8 with a value of 1.03 (Fig. 3A). This finding indicates that OTA contamination levels in most tested products fall within the safe range defined by regulatory standards. Among the tested products, corn showed the highest mean pollution index of 0.16, while the distribution of risk remained highly heterogeneous. A total of 98.7% of corn samples had values below 1.0, and the single extreme outlier Corn 8 with a value of 1.03 significantly increased the overall mean value for this commodity (Table S5). This pattern demonstrates that corn OTA contamination presents a generally low background with episodic high intensity risk profile, which requires enhanced monitoring and targeted control measures for such high-risk samples. In comparison, peanuts, soybeans and wheat displayed more concentrated distributions of pollution index values, with all values staying below 0.4 and confirming manageable contamination risk.

The exceedance rate analysis showed that the overall rate across all samples was only 0.31%, corresponding to a low-risk classification. At the commodity level, only corn presented a positive exceedance rate of 1.3% (Fig. 3B and Table S6). Although this rate is numerically low, special attention should be paid due to the significant role of corn in the regional dietary structure. No exceedance was observed in peanuts, wheat or soybeans, which indicates these products carry relatively low risk of OTA contamination under current conditions.

3.3 Margin of exposure risk assessment

Exposure margin assessment was performed on positive samples to assess the carcinogenic and non-carcinogenic risks of OTA. Varied risk profiles were identified across different products and age brackets. The comparison between the confidence limit at the carcinogenic baseline dose and the estimated daily intake revealed that corn samples exhibited the highest potential carcinogenic risk (Fig. 4A). Specifically, two corn samples showed tumor MOE values below the safety threshold of 10000 for adults aged 18–44 (Table S7). However, it should be emphasized that these values were derived from only two individual samples, and the MOE approach is inherently conservative by design. Therefore, while these findings raise a concern that warrants further surveillance, they should not be overinterpreted as evidence of established carcinogenic risk at the population level. Extended monitoring with larger sample sizes is needed to confirm whether this pattern is consistent over time and across locations.

For non-tumorigenic risk assessment, all samples showed values above the safety threshold of 200, indicating negligible non-carcinogenic health risks (Fig. 4B). Age-dependent differences were observed.

Younger age groups generally had lower margin of exposure values due to higher relative intake and lower body weight. Soybean samples maintained safe values even at relatively high OTA concentrations because of low dietary consumption levels. The overall risk pattern indicates that carcinogenic potential is the primary health concern related to OTA exposure. Margin of exposure values present a non-linear relationship with OTA concentration, and dietary intake rate acts as a key modifying factor. The notable risk difference between corn and soybeans is mainly attributed to the higher consumption rate of corn, highlighting the combined effects of contamination level and dietary habits on actual health risk.

3.4%PTWI risk assessment

Long-term cumulative exposure risk of OTA in grain products from the Yangtze River Delta region was evaluated using the provisional tolerable weekly intake. Risk level was expressed as the percentage of estimated weekly intake relative to the provisional tolerable weekly intake. The age-dependent changes in percentage values across different grains are presented in Fig. 5A. The horizontal line marks the safety threshold at 100%. Corn showed the highest risk profile, with percentage values peaking at 100% in the 18–44 age group and remaining elevated in adjacent age brackets. To clarify the influence of the single extreme outlier (corn sample, 5.16 ng/g) on the %PTWI estimates, a sensitivity analysis was performed for adults aged 18–44 under five scenarios: mean including outlier, median (P50), 75th percentile (P75), 95th percentile (P95), and mean excluding outlier, with results presented in Table S8. The mean %PTWI including the outlier was 104.3%, exceeding the safety threshold; however, the median (51.9%) and P75 (95.1%) were both below the threshold, while P95 (292.4%) reflected an extreme exposure scenario associated with highly contaminated batches. After excluding the outlier, the mean decreased to 51.5%, consistent with the median, indicating that the 104.3% value is primarily driven by a single outlier and does not represent the typical OTA exposure level from corn in this region.

Furthermore, given that the daily ingestion rates used in this assessment were derived from national average consumption data, and that actual corn consumption in the Yangtze River Delta is considerably lower than the national average, the %PTWI estimates for corn, particularly the 104.3% value for adults aged 18–44, may overestimate the actual exposure of local residents. Nevertheless, the relative ranking of corn as the grain type with the highest OTA contamination and associated risk among the four commodities examined remains robust, supporting its prioritization in routine monitoring programs.

Wheat showed moderate percentage values, peaking below 100% in the 13–17 age group (Table S9). Peanuts and soybeans maintained low and stable percentage values across all age groups. The spatial distribution of risk values is shown in the heatmap, where increasing color intensity corresponds to higher risk levels (Fig. 5B). High-risk zones were concentrated in corn samples, especially among the 18–44 and 60 and above age groups, confirming the presence of values exceeding 100%. Wheat showed mild risk elevation only in older age groups, while peanuts and soybeans remained at low risk across all ages. The summary of multi-dimensional risk assessment indicators is presented in Table 3.

Overall, the cumulative exposure risk of OTA in regional grain products is generally manageable, but notable variations exist among products and population groups. Among the grains tested, corn exhibited relatively elevated exposure levels. Multiple corn samples showed percentage values above 100% in all

age groups, with adults aged 18–44 representing the age group with the most pronounced exposure, indicating a need for attention to long-term health effects. Although peanut samples did not exceed regulatory limits, potential cumulative effects from highly contaminated samples still warrant consideration. Wheat and soybeans showed low percentage values and negligible health risks due to low contamination levels and limited dietary intake. Younger age groups appeared more sensitive to OTA exposure, with percentage values typically two to three times greater than those in older groups. This trend is consistent with the results of the margin of exposure assessment and further suggests that children and adolescents represent a population subgroup deserving particular attention regarding dietary OTA exposure.

Table 3
The summary of multi-dimensional risk assessment indicators.

Type		Wheat	Peanut	Corn	Soybean
Positive rate (%)		7.4	9.3	16.7	13.9
Pollution index (PI)		0.07	0.11	0.16	0.10
Exceedance rate (%)		0	0	1.3	0
Tumor MOE	Min	12368	2145947	1419	69851
	Max	834556	22354167	320983	10730000
Non-tumor MOE	Min	4035	700023	483	22786
	Max	272238	7292083	104707	3500200
%PTWI	2–6	3.95	0.11	13.78	0.90
	7–12	5.10	0.22	18.11	1.15
	13–17	32.93	0.16	15.49	0.92
	18–44	28.59	1.26	104.30	6.26
	45–59	13.88	0.59	52.40	3.04
	≥ 60	20.31	0.92	79.69	4.86

3.5 Risk management advice

Based on the current OTA contamination data and multidimensional risk assessment results, targeted monitoring and management of OTA in grain products could be appropriately strengthened in the Yangtze River Delta region. Corn, as a grain type with relatively higher associated risk, may be prioritized in routine monitoring programs, with regular tracking of its contamination trends to facilitate timely identification of potential risk points. In addition to OTA, joint surveys of multiple mycotoxins and contaminants in grains could also be conducted when appropriate (Liao et al., 2023), given the possible co-occurrence of various contaminants and their combined effects. The integrated application of multi-

indicator monitoring and risk assessment approaches contributes to a more comprehensive understanding of contamination profiles. Overall, the establishment of a "monitoring–assessment–tiered management" framework would be beneficial for enhancing the whole-process management capacity for mycotoxin contamination and providing technical support for regional food safety assurance.

3.6 Uncertainty analysis

In this study, a systematic assessment of dietary exposure risk to OTA from grain products was conducted using an exposure assessment model (Nugraha et al., 2025). However, several sources of uncertainty inherent to the evaluation framework should be acknowledged. These relate to multiple aspects, including OTA occurrence and detection, consumption data, exposure modeling, toxicological parameters, and sample representativeness. Regarding the analytical methodology, the use of a single detection method with limited cross-validation may introduce certain bias, and the complexity of food matrices could potentially affect detection accuracy. Consumption data were based on population averages rather than individual-level variability, which may lead to either overestimation or underestimation of actual exposure for specific subgroups. The exposure assessment is also constrained by the wide concentration ranges observed in certain grains, particularly corn, and by the application of a single-contaminant model that does not account for possible interactive effects among co-occurring mycotoxins. Toxicological benchmarks derived from animal studies carry inherent uncertainties due to interspecies differences in metabolism. Furthermore, the sampling was confined to the Yangtze River Delta region and to a specific study period, which may limit the spatiotemporal generalizability of the findings. Despite these limitations, a conservative approach was consistently applied throughout the assessment to avoid underestimation of potential risks. Therefore, the relative risk rankings across grain categories are considered robust and provide a sound scientific basis for implementing tiered control strategies.

4. Conclusion

In this study, 324 grain samples collected from the Yangtze River Delta were analyzed for OTA contamination using LC-MS/MS, and health risks were systematically evaluated through multi-index approaches including PI, ER, MOE, and %PTWI. Among the four grain types examined, corn exhibited the highest OTA contamination, with a detection rate of 16.7% and the only PI value (1.03) exceeding the regulatory limit. A single extreme outlier of 5.16 ng/g was identified in one corn sample, which substantially elevated the mean contamination level and suggested the presence of localized contamination hotspots. Risk estimates indicated that the mean %PTWI for corn in adults reached 104.3% based on national average consumption data, exceeding the safety threshold, while two corn samples showed MOE values below 10,000. However, these elevated estimates were primarily driven by the single outlier and should be interpreted with caution, particularly given that regional corn consumption in the Yangtze River Delta is considerably lower than the national average. Nonetheless, the relative risk ranking of corn as the highest among the tested grains remains robust, supporting its prioritization in routine monitoring programs. In contrast, wheat, peanuts, and soybeans exhibited

relatively low OTA levels and posed acceptable health risks across all age groups. While the overall OTA contamination status in the region appears generally manageable, the MOE and %PTWI results still warrant continued surveillance and timely regulatory adjustments for grains with elevated contamination potential. Given the possible co-occurrence of multiple mycotoxins in cereals, future studies should extend beyond OTA to include comprehensive assessments of other prevalent mycotoxins and their combined effects. Overall, this study demonstrates the practicality of an integrated detection–assessment–tiered management framework for effective mycotoxin pollution control.

Declarations

Supplementary information

Supplementary information to this article could be found online.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author Contribution

Guangyun Chen: Investigation, Writing-Original Draft. Junjian Li: Methodology, Validation. Guizhu Wu: Software, Methodology. Daolin Du: Conceptualization, Visualization. Ming Li: Funding acquisition, Project administration.

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Data availability

Data will be made available on request.

CRediT authorship contribution statement

Guangyun Chen: Investigation, Writing-Original Draft. **Junjian Li:** Methodology, Validation. **Guizhu Wu:** Software, Methodology. **Daolin Du:** Conceptualization, Visualization. **Ming Li:** Funding acquisition, Project administration.

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Figures

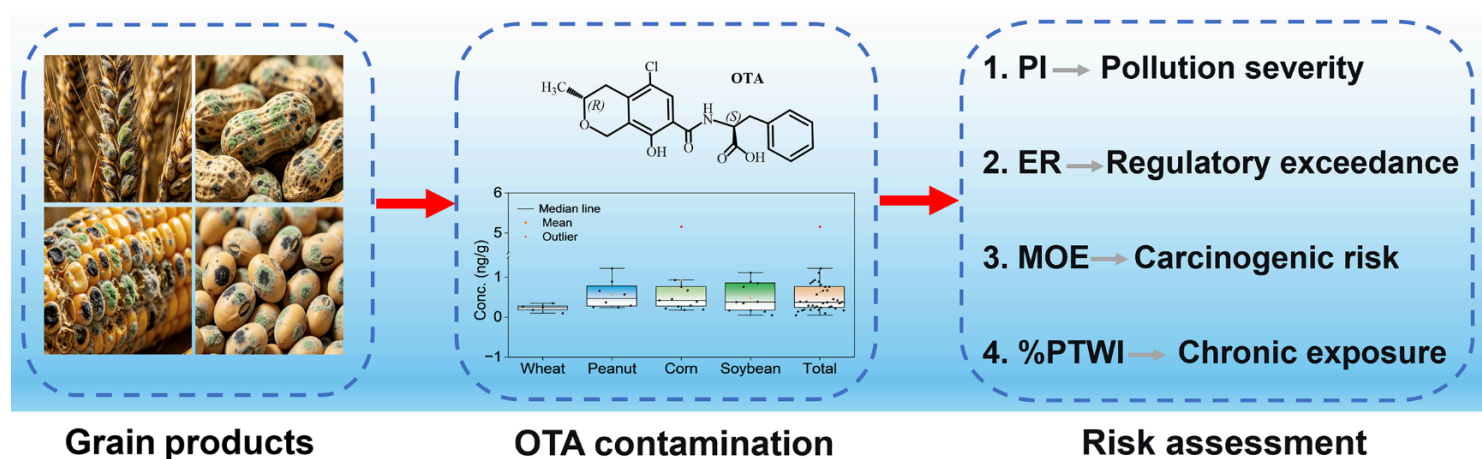


Figure 1

The distribution of OTA contamination concentrations in different grain types.

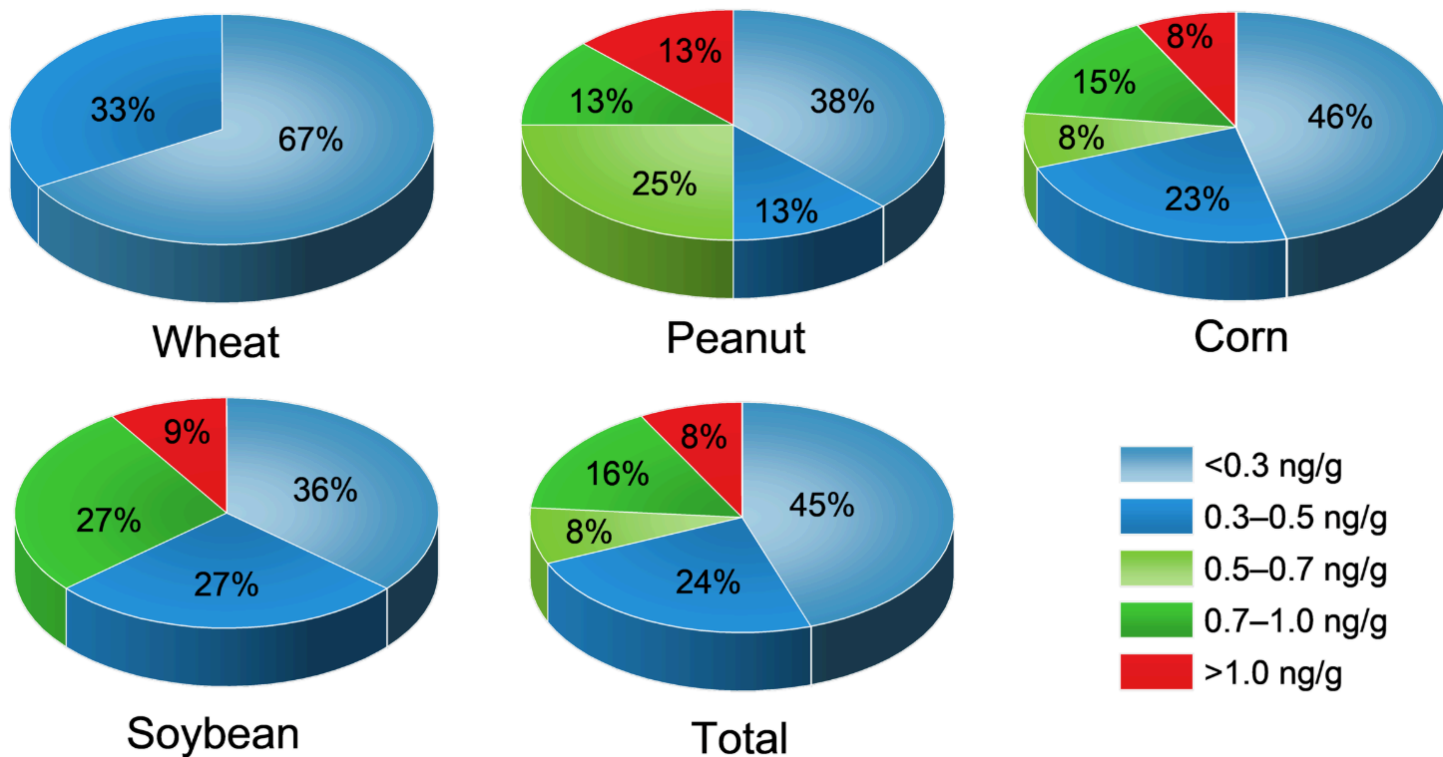


Figure 2

The OTA contamination concentrations in different grain types.

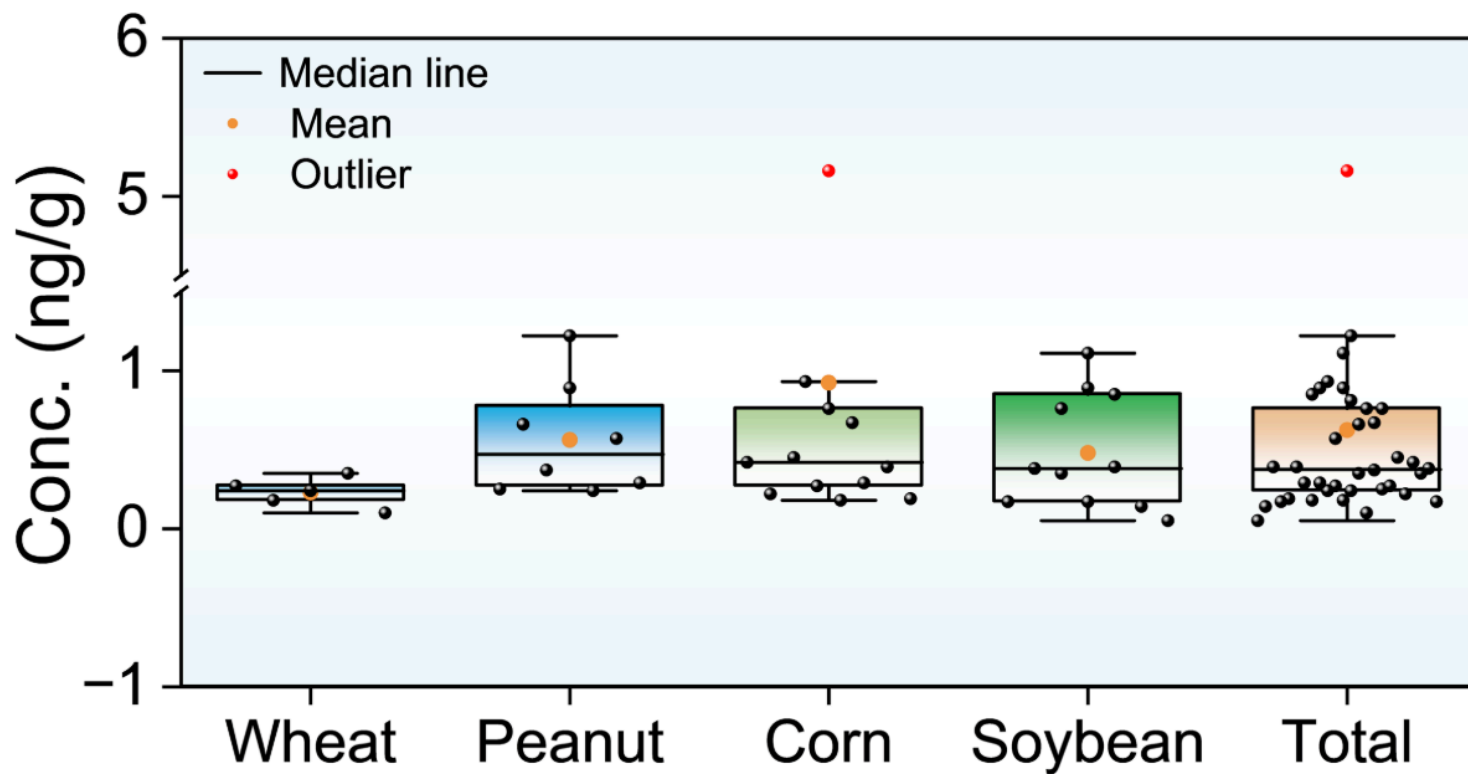


Figure 3

The PI and ER of OTA in different grain samples. (A) The PI values of individual samples. (B) The contamination profile shows the proportion of samples in different contamination categories.

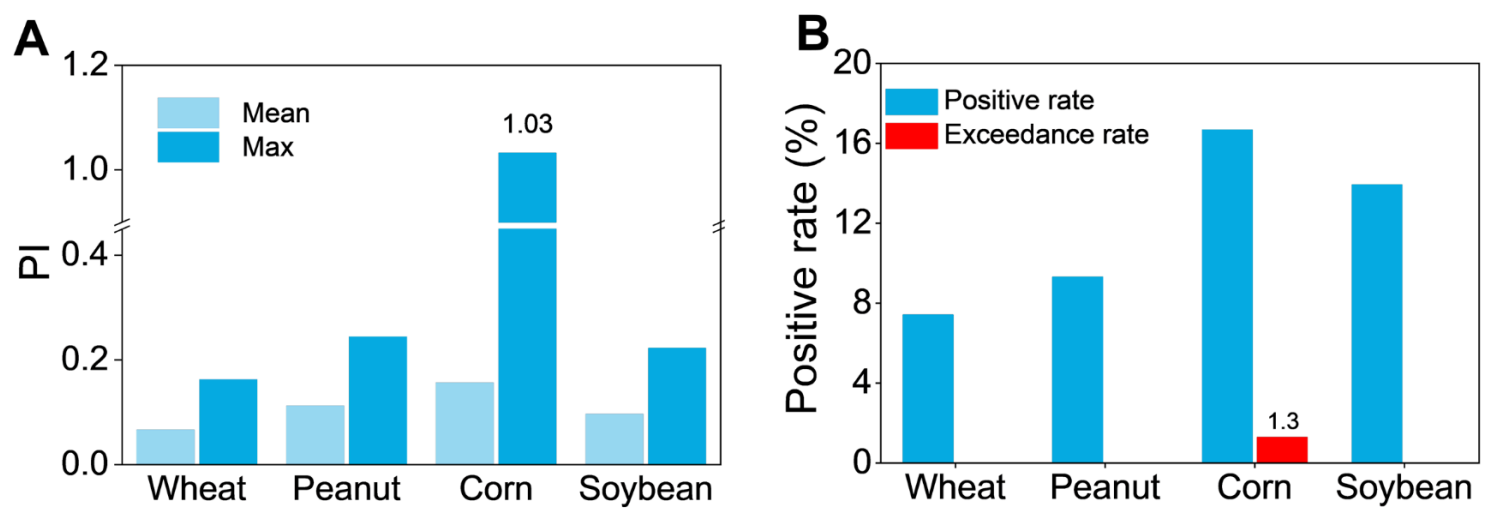


Figure 4

The MOE of OTA-positive samples for different age groups. (A) Tumor MOE values, (B) Non-tumor MOE values.

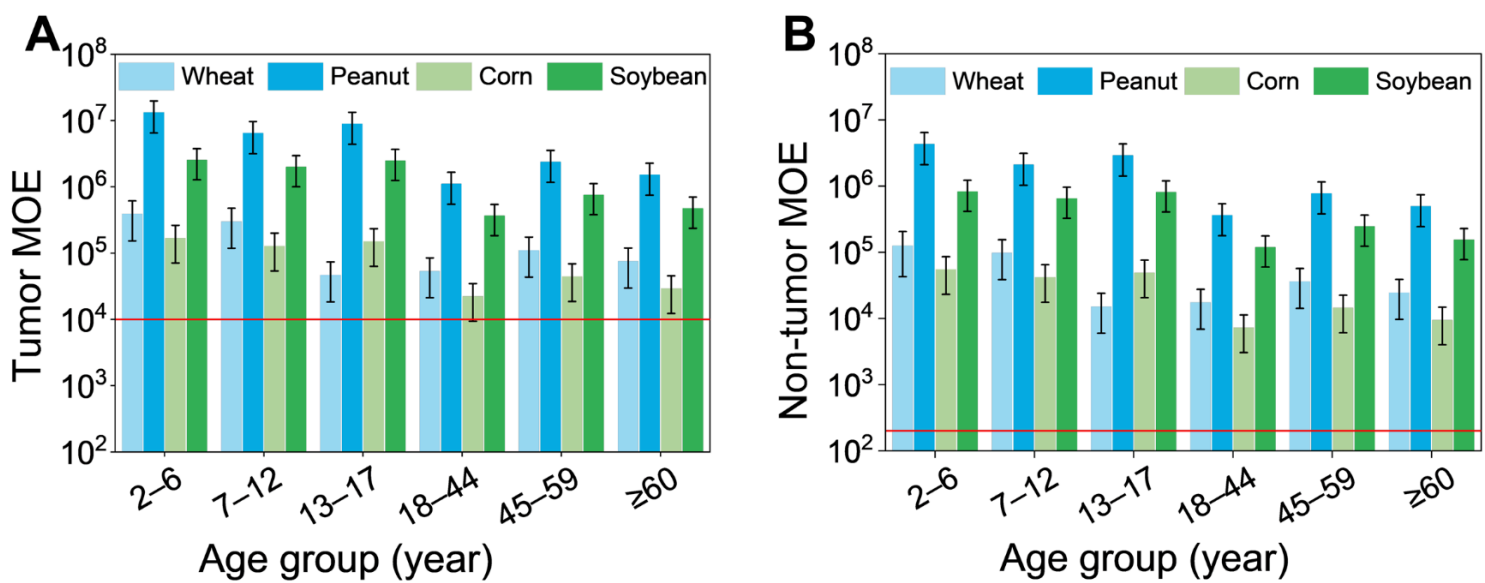


Figure 5

The %PTWI of OTA-positive samples for different age groups. (A) Variation trend of %PTWI, (B) Heatmap of %PTWI.

Supplementary Files

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